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THE COMPUTER SIMULATION OF DIGITAL RECORDING SYSTEMS

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Summary

Digital recording systems for television are becoming more widely used in the broadcasting industry. Traditionally, the design, evaluation and performance monitoring of such recorders has relied on conventional laboratory methods and equipment. This Report presents an improved approach to these tasks based on the use of a computer to process electrical signals which have been captured from the circuits of the recording system under test.

This computer simulation technique provides a clearer insight into the factors affecting the performance and reliability of digital recording systems, so that quantitative measures of confidence in them can be derived before valuable programme material is finally stored. The simulation also provides a convenient framework for optimising recording system design.

Index terms: *DVTR; performance; simulation; record/replay processing*

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THE COMPUTER SIMULATION OF DIGITAL RECORDING SYSTEMS

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1. INTRODUCTION

This Report describes a technique for the detailed analysis of the properties of digital recording systems. The analysis has been carried out by developing a series of programs on a computer which simulate the behaviour of the elements found in prototype, or commercially designed recording systems. These programs are used to process electrical record or replay signals which have been intercepted from the circuits of a recorder using high speed waveform *digitising equipment*, as illustrated in Fig. 1. Alternatively, the programs can be used to process record signals that have been artificially generated within the computer, by other software simulating the fundamental physics of the record–replay process. The results from such processing provide a new insight into the quality of performance of recorders, and can be used to identify the contribution to that quality made by different aspects of the recorder's operation. The simulation also provides a convenient framework for experimenting with recording system design, so that the function of electronic circuits can be optimised. It is perhaps a shame that this technique was not available during the BBC's early experimentation with digital television recording[1, 2, 3, 4, 5].

Much of the experimental work conducted so far with the simulation system has involved high density, digital magnetic tape recorders as used for the digital recording of television pictures. The potential benefits of digital recording have long been appreciated both by broadcasters and commercial broadcast equipment manufacturers. The major advantages are that editing and multi-generation recording of programmes can be achieved with no loss of technical quality. However, the cost of major drama productions, per hour of programme, is many times the cost of the

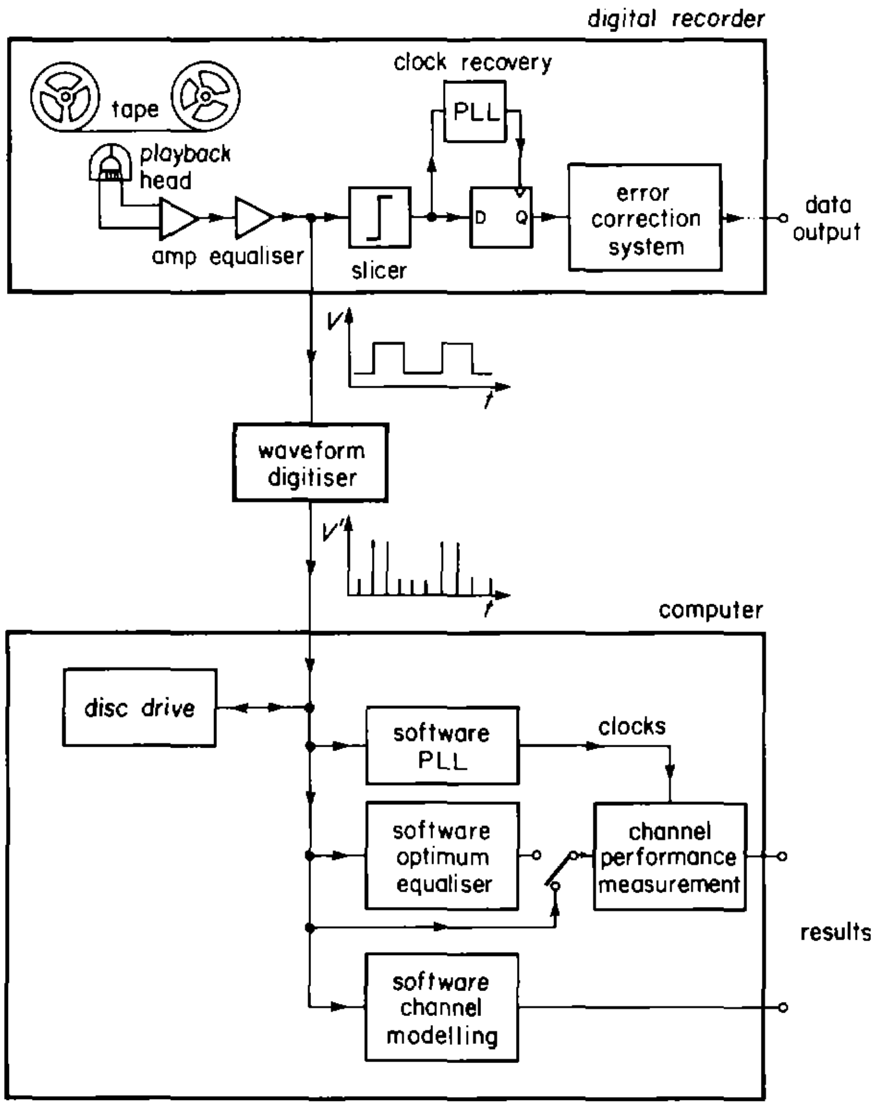


Fig. 1
Simulation of a typical recording channel.

recording equipment on which the programme might eventually be stored, (and many thousands of times the cost of the recording medium). Before such programmes can be consigned to new recording formats and perhaps archived, the broadcaster must confirm that these advantages are achieved. It must be demonstrated that the new format is reliable, and that it could be widely adopted and supported for a number of years. Some measure of confidence is required as to the reliability of the recording mechanism, and how this reliability will change as machines age and components wear. An indicator is needed which shows the safety margin that is available for deterioration in a recorder's internal performance, after which the much acclaimed potential for error-free recording and replay would no longer exist.

The simulation system described in this Report has been developed to provide quantitative measures of confidence in digital recorders, by looking at electrical signals inside them. In the following sections, the requirements of this system are outlined, together with the configuration of computer hardware and software which comprise it. Several aspects of recorder performance are identified as being especially important for broadcasting, and a method is described for comparing and quantifying the relative impairments caused by each to the overall operation of a recording system. A means of estimating the safety margin (outlined above) is described, along with a brief selection of results from the investigation of commercially available digital video tape recorders. In general, the simulation provides a flexible way of making measurements of the properties of digital recording channels, with a degree of detail that is difficult or impossible to achieve with more conventional techniques.

2. OBJECTIVES/REQUIREMENTS OF THE COMPUTER SIMULATION

Improved tools for investigating digital recording systems are needed because there is a trend towards higher recording density. This trend has several consequences:

- The basic recording medium is used in a way that pushes the physical recording process closer to its theoretical limits.
- The tolerances of electrical and mechanical components become smaller.
- The design of recorders becomes increasingly complex.

As suggested in the introduction, the simulation system has been developed to satisfy this need for two broad classes of application: one concerns the performance evaluation of commercially available digital recording equipment; the other concerns aspects of digital recording system design.

2.1 Performance evaluation of digital recorders

In this application, the simulation system serves to provide quantitative measures of the performance of a particular digital recorder, given the operating conditions under which it would be used to produce and store television programmes. Probably the most important attribute of a digital recorder is its ability to reproduce the data that was originally recorded without errors. So the most basic indicator of a recorder's performance is the rate of errors in the replayed data.

In the case where a recorder is working well (i.e. the replayed data is error free), we need the ability to predict what deterioration in the internal status of the machine can be tolerated before errors begin occurring in the output. In the case where errors are occurring in the replayed output of a machine, we need the ability to identify which of the many factors that control a recorder's overall performance are responsible.

2.1.1 Safety margin

The presence of an error-correction system in modern digital recorder design complicates the interpretation of replayed error rates as an indicator of performance. Error correction reduces the output error rate to near zero during normal channel operating conditions. It does so at the expense of making the variation of error rate with the channel operating conditions very rapid near the point of error overload (as illustrated in Fig. 2). So when a recorder fails, the error rate could suddenly change from essentially zero to many errors, with apparently little warning. It is for this reason that an indicator of the safety margin of the working point of a recorder from the point of error overload is needed. This gives a measure of confidence in the recorder's reliability.

2.1.2 Operational conditions

The BBC uses its tape recording equipment for both producing as well as storing programmes. Tape editing is used extensively during programme production, under operational conditions which demand that a recording on any one particular machine can be replayed and edited equally well on any other machine (perhaps from a different manufacturer).

If error-free performance is to be achieved, these operational conditions impose even more

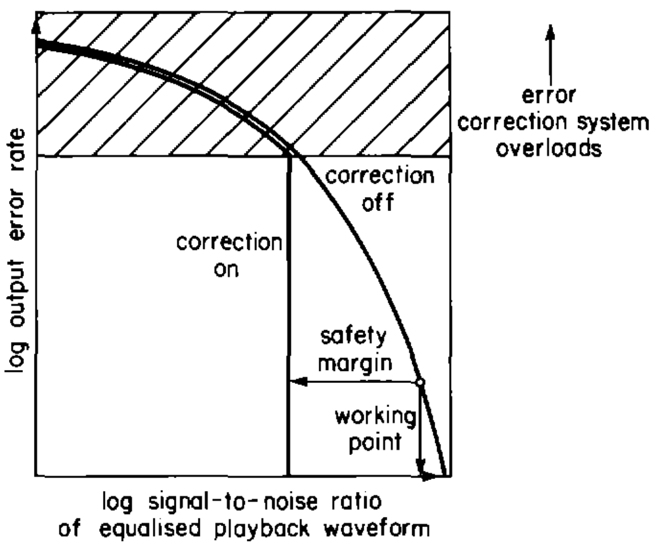


Fig. 2 - Schematic variation of error rate with channel operating conditions.

stringent constraints on the quality of the recorders used (more so than when just recording and replaying un-edited tapes on the same machine). The safety margins referred to above must also be evaluated under conditions where tapes have been edited, and where they have been exchanged between different machines.

2.2 Digital recording system design

In the design of digital recording machines, the objective of using computer simulation is to provide a framework in which different design strategies can be tested, *under realistic conditions, without the need to* build dedicated electronic hardware each time. When individual modules in the design of a recording channel are simulated in computer software, their configuration can easily be varied, and their performance optimised.

2.3 Recording fundamentals

If the understanding of the fundamental physics of recording can be extended, then recording systems can be designed to use more efficiently the potential recording capacity of a particular medium. This will lead to increased recording density, or reliability, or perhaps both.

The optimum configuration of a recorder can only be achieved when the properties of the underlying recording system are well understood. Physical processes occurring in the recording mechanism, such as the magnetic fields surrounding the recording heads or the magnetisation in the recording medium, can be modelled mathematically, *and simulated in computer software.*

Recorded or replayed signals produced by these models (or conditions predicted by them), can be compared with appropriate signals (or conditions) in a real recorder. These comparisons are very easy to make for the simulation system described in this Report, because signals from real recorders are captured, digitised, and finally stored on the same computer that is used to develop the software models.

If the models are refined such that their predictions closely match the situation in real recorders, we obtain a much deeper understanding of the process being simulated. This information leads to recorder design which is better optimised to match the recording mechanics and medium used.

3. COMPONENTS OF THE SIMULATION SYSTEM

The simulation system consists of waveform digitising hardware and a computer with software. The computer is used both to control the digitising hardware during experiments, and to develop and run the simulation software (Fig. 1).

3.1 Waveform digitising hardware

The function of the waveform digitising hardware is to intercept electrical record or replay signals from some point in a recorder's internal electronic signal chain. Such signals are digitised at high speed, and later transferred to the computer to be permanently stored on computer disc. The digitised waveforms are subsequently processed by the simulation software. The digitiser consists of an analogue-to-digital converter (ADC), a demultiplexer, and random access memory (RAM), as shown in Fig. 3. The demultiplexer serves to reduce to a practical value the rate that the high speed samples from the output of the ADC are written to the RAM.

The digitiser is connected to the host computer by a typical computer interface, such as GPIB (the General Purpose Interface Bus, or IEEE 488 interface). Captured waveforms are then transferred to the computer in non-real-time, to be stored permanently on the computer's Winchester disc.

Also shown in Fig. 3 is a digital-to-analogue converter (DAC) connected to the RAM via a multiplexer. This enables waveforms output from the digitiser to be inserted back into the circuits of a recording system. These may be waveforms previously captured from the same recorder, or from a different recorder. Alternatively, they may be waveforms that have been processed by the computer in some way, or waveforms artificially generated by it.

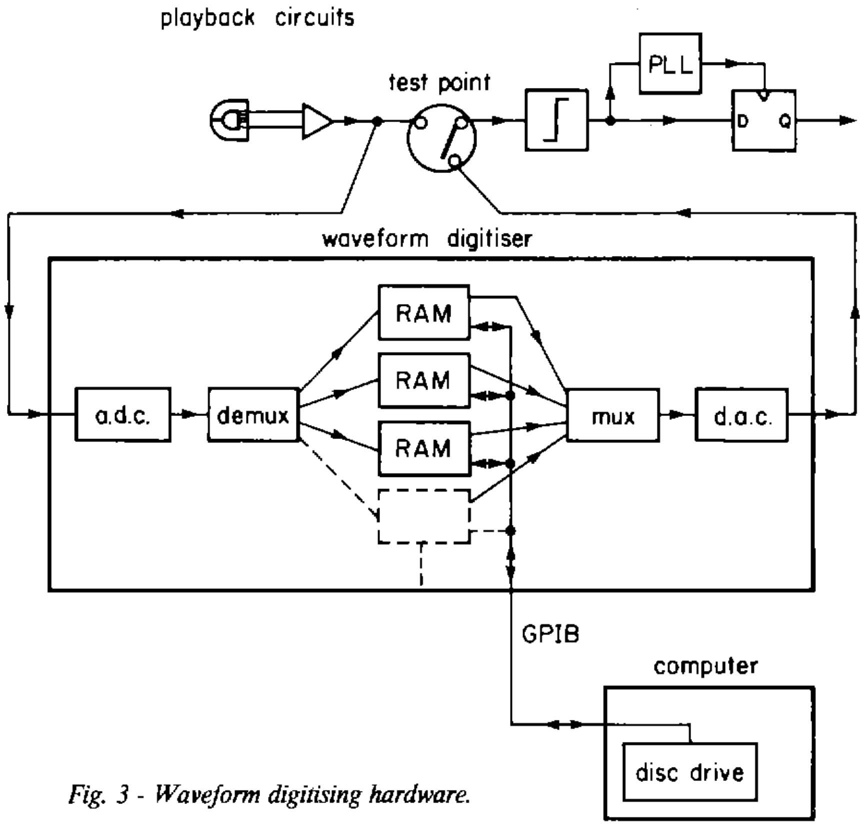


Fig. 3 - Waveform digitising hardware.

3.1.1 Sampling requirements

The requirements of the digitising hardware depend on the recording systems under investigation. Modern digital video tape recorders (DVTRs) used for broadcasting employ record/replay signals with bandwidths of 50 MHz or more. Any simulation software which performs waveform reconstruction (interpolation) of the digitised signals requires that the Nyquist sampling criterion was satisfied during that signal's capture, so that signal aliasing does not occur. To ensure that distortion caused by aliasing does not significantly impair measurements made on captured waveforms, the waveform digitising equipment developed by the BBC samples at 162 MHz. However, even this high sampling frequency may soon need to be raised to cope with the next generation of DVTRs designed for recording High Definition Television.

To ensure that measurements made on the digitised waveforms accurately reflect the properties of the recording channel, adequate sampling precision is needed. The quantising noise introduced by the ADC must be considerably below the level of the noise in the channel before sampling. The distortion introduced by the ADC (especially non-linear distortion) must be kept as small as possible. In practical terms, six bits of quantising accuracy has been found adequate for broadcast DVTRs, although eight bits would be preferred.

The final sampling requirement for the waveform digitiser concerns the length of the digitised waveform that can be held in the RAM. Broadcast DVTRs almost universally employ helical scanning of the tape (Fig. 4). Interesting properties of the tape transport (the mechanical assembly of tape guiding mechanism, and recording heads) are often reflected in replayed signals from the ends of the helical tracks. The digitiser should have sufficient capacity to store captured signals lasting at least one, preferably several, helical track lengths during record or replay. Other properties of a video recording system may be reflected over a period lasting a television field or frame. For this reason the BBC digitiser was equipped with sufficient RAM to store a sequence lasting 40 ms.

3.2 Computer software

Extensive computer software has been developed to perform four tasks:

1. To control the waveform digitising equipment during signal capture, and in some experiments to remotely control the recording system from which the signals are being intercepted.

2. To measure or estimate aspects of the recording system's performance, in terms of the contribution of the different aspects to the overall susceptibility to making errors.

3. To simulate the behaviour of circuit elements in the recorder's design so that their function can be optimised.

4. To model the fundamental physical processes in the recording transport.

To help perform these tasks, additional computer programs have been developed for graphical display of the shapes of captured waveforms, eye diagrams, power spectra and other processed signals.

3.2.1 Structure

Almost all the software is written in Hewlett Packard extended Pascal language, and has made extensive use of its modular structure. The total size of the software in the simulation has grown to exceed 40000 lines of Pascal source code, and it will continue to grow during the investigation of new recording systems. Maintenance of software of this size, with contributions made by several authors has been eased by encouraging a standard syntactic style with additional emphasis on creating programs which read as easily as English text (within the bounds of the Pascal language).

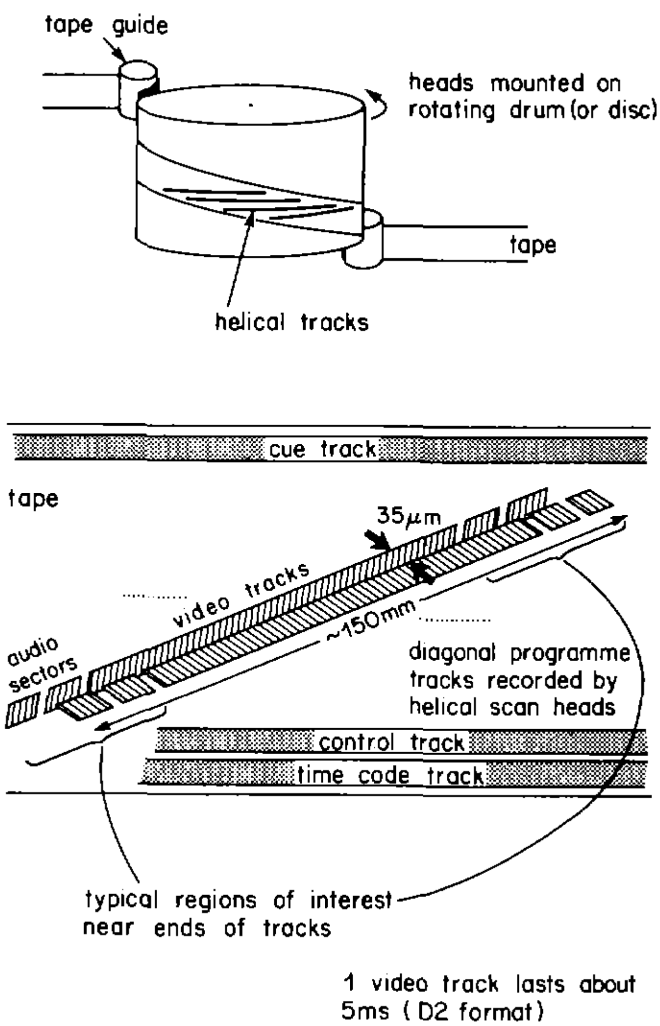


Fig. 4 - Helical scan tape format (D2 shown).

Digitised waveforms are stored as files on the computer's disc. As these files are processed, new files are created and an audit trail is produced which describes the chain of events that lead to the creation of any particular file. It is safest for this audit trail to be stored as an integral part of the files containing sampled waveforms. Thus it is impossible for an audit trail to become accidentally detached from its associated waveform. In addition, the information describing the content and numeric format of a waveform file resides inside it, so that process pipelines can be constructed, as described below.

3.2.2 Process pipeline

Computers which run UNIX operating systems offer an additional dimension to waveform processing for simulation. A job which simulates a certain series of processes can be constructed as a Pascal program, compiled, linked and then executed, in the traditional fashion. Alternatively, the job could be constructed by pipelining a series of pre-prepared programs using the operating system. This latter technique is particularly useful for quick, interactive experiments.

4. ELEMENTS OF THE SIMULATION SOFTWARE

The elements required for a software simulation of a typical digital recording channel are illustrated in Fig. 5. The stream of data to be recorded is first coded using an error-correction system. The new sequence of data is often re-ordered in time (shuffled or interleaved) to improve the error-correcting power for long bursts of continuous errors, typically caused in magnetic tape systems by dropout*. The error-protected data is often channel coded (to better match its spectral content and statistical properties to those passed by a magnetic recording channel) before being further processed by a pre-equaliser (which can include both linear and non-linear pre-distortion of the data) and finally applied to the record heads.

On replay, the waveform from the replay heads is amplified, before being equalised (which again can be a mixture of linear and non-linear filtering). Clock timing information is then recovered and used to produce a raw data stream from the equalised waveform, which is finally channel decoded, re-ordered in time and error corrected. Those errors

* A dropout is a temporary interruption in the replay signal caused by a blemish in the recording medium, or dirt between the record or replay heads and medium.

which cannot be corrected are often concealed, using predefined properties of the recorded (video) signal.

One area of particular interest to a broadcaster is the tape transport part of a recorder, from the pre-equalisers on the record side to the post-equalisers on the replay side. For this reason, the development of simulation software has been concentrated in this area. Not all of the components required for a complete recording system have been simulated in software at the time this Report was being prepared.

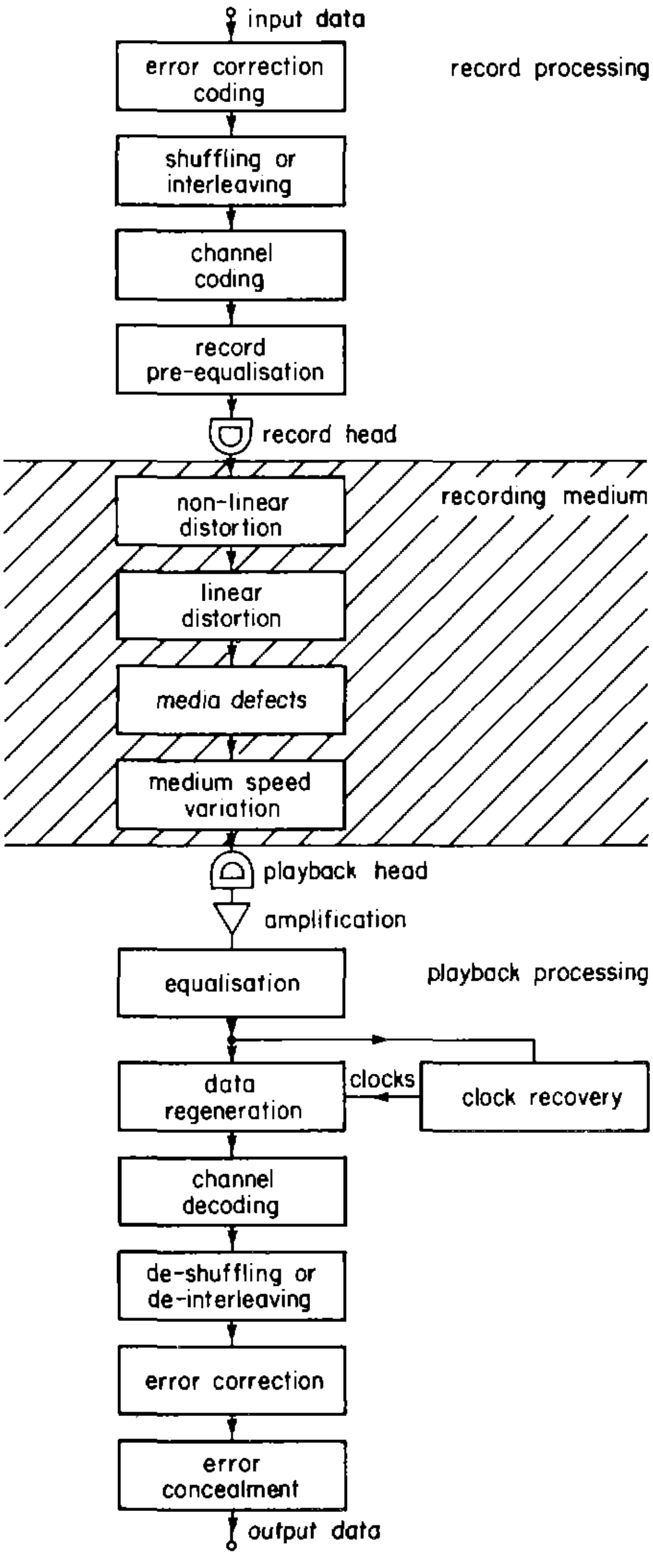


Fig. 5 - Software components of a digital recording channel simulation.

4.1 Pre-equalisation

There are two requirements of a pre-equalisation system for magnetic recording. These are to compensate for the effects of linear and non-linear distortion which occur during the recording process, which could otherwise lead to an increase in the incidence of errors during replay*. Such effects become more important as the density of the recorded data on the medium is raised, when the magnetic fields created by neighbouring data bits begin to affect each other during recording[6, 7]. The result on replay can be an apparent shift in the timing of data bits depending on the particular surrounding data pattern. One method of compensating for these effects is to pre-distort the record waveform to exactly counter-balance the distortion during the recording process.

4.2 Model of recording channel

Models of recording channels take a variety of approaches, and span a considerable range in complexity. There are models which use the basic physics of magnetism to predict recorded magnetisation on tape and reproduced waveforms[8]. However, much of the work conducted using the simulation system to date has involved evaluating complete recording systems. For this application, a method of modelling the recording channel as a whole has been developed, which describes the channel using a transfer function containing linear and non-linear components. The transfer function is based on experiment, in that the magnitudes of the various linear or non-linear components are derived from averages of measurements made on real channels. The method is described in more detail in Section 5.

4.3 Post-equalisation

Post- or replay equalisation attempts to reduce the impairment to the reproduced waveform caused by a variety of distortions in both record and replay.

Traditionally, equalisation has been a correction for the distortion to the frequency response of the signal at the output of the replay head (as described in Section 5.1.3).

* The basic amplitude transfer characteristic of the magnetic recording process is quite non-linear. This is not the prime concern here. Since the record waveform is approximately a two-level signal, the recorded magnetisation will be approximately two-state. To first order, amplitude distortion does not occur.

The trend towards higher recording density has lead to the use of more complex equalisation schemes, which raise the performance of the raw recording channel. Considerable software has been developed for simulating the effect of equalisers of various designs, and for optimising the design to match the properties of the particular recording system. Several designs of interest include optimised linear equalisers, quantised feedback equalisers, decision feedback equalisers, adaptive equalisers and non-linear equalisers.

4.4 Clock recovery

Clock timing information is almost never recorded. It would take up valuable space available for data. Timing information is recovered from the replayed waveform before being used to reconstruct the raw data values that it contains. A phase-locked-loop is often used.

The simulation software contains phase-locked-loops (and associated equalising filters) for timing recovery. The order and characteristics of the loop can be varied very conveniently.

4.5 Measurement software

The post-equalisation and clock recovery software modules can be used in sequence to process waveforms captured from the replay circuits of a recorder using the digitising equipment. Using equalisation and clock recovery, the data that was originally recorded can be regenerated in software. At this stage it is then possible to make measurements indicating the performance of the recording channel. Software has been developed to monitor various aspects of tape transport performance including the estimation of error rates, the measurement of frequency responses, and the investigation of the physical accuracy of recorded track patterns on tape. These functions are considered in more detail in the following two sections.

The measurement software includes complex interpolators and sample-rate changing routines in its operation. Interpolation is required for accurate signal measurement at an arbitrary point in a sampled waveform. Sample-rate changing is required during the calculation of the frequency response of a channel (from a digitised replay waveform together with the software recovered data).

5. ESTIMATING DIGITAL RECORDING CHANNEL PERFORMANCE

A wealth of information can be deduced about the performance of a recorder from signals within it that have been captured by the digitiser. Of all the possible points at which signals can be intercepted in the signal chain, one point on the replay side reveals the most about the performance of the tape transport. This point is at the output of the replay equalisers, but before slicing occurs (Fig. 1). Once slicing has taken place, much of the analogue information conveying the properties of the transport has been removed.

A great many components contribute to the performance of a digital recording channel. A means for identifying poor stages in the recording chain, and for comparing the relative sizes of impairments introduced by each would be very valuable to both system designers and users. In the following sections, some important sources of impairment in digital recording are discussed, along with a means for comparing their relative sizes.

5.1 Sources of impairment

In high density magnetic tape recording, the sources of impairment to the performance of a recorder can be classified into three groups:

1. Those associated with defects in the recording medium.

2. Those associated with the mechanics of the tape transport, such as the tape guiding system.

3. Those fundamentally associated with the magnetic record–replay process, and the recovery of data from the waveform reproduced from tape.

5.1.1 Recording medium

The record and replay heads must stay in contact with a uniform layer of magnetic material for successful operation. If the recording medium should be non-uniform, either physically or magnetically, the record or reproduce process can be interrupted (known as a dropout). This can also happen if the heads are displaced out of contact with the recording medium by dirt. Contact between the heads and the tape surface must be maintained to within a fraction of a recorded wavelength (which for current machines is a distance measured in hundreds of nanometres).

When tape defects or dirt are encountered, the effect on data reproduction can be drastic. A single blemish can cause thousands of consecutive bits to be replayed in error. This is illustrated in Fig. 6, where a section of digitised (equalised) waveform is shown from a tape replayed on a D1 DVTR, where there is a dropout caused by a small bump in the magnetic coating, approximately 1 mm in diameter. About

10000 bits have been corrupted during the dropout, which is equivalent to a length of about 4.5 mm along the tape*. The figure also suggests that there is some oscillation of head-to-tape contact after the initial disturbance.

Tapes can also shed their magnetic coating, which may become lodged in the heads. This interferes with the physical contact between heads and tape, reduces the magnetic field output from a record head and degrades the replayed signal from a reproduce head.

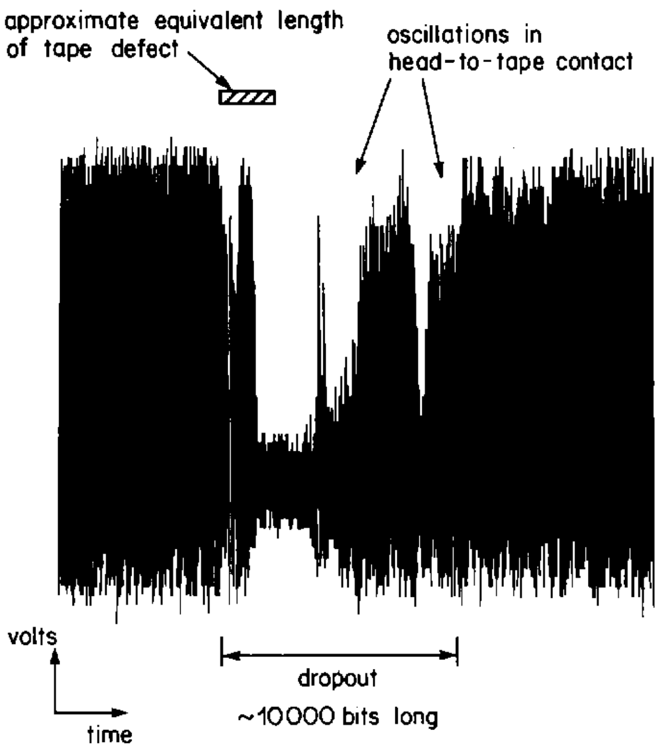


Fig. 6 - Replayed waveform during a dropout.

5.1.2 Tape transport mechanics

For the tape transport part of a recorder, the accuracy and consistency with which the tape can be guided past the heads, at controlled tension, from spools or a cassette, is of paramount importance. The trajectory of the replay heads along the tape must correspond precisely to the path taken when recording took place (to within a fraction of the spacing between adjacent recorded tracks). For helical scan recorders of type D2[9], this trajectory must be accurate for tracks spaced 35 micrometres apart and 150 millimetres in length. This situation is further complicated when using thinner tape, which has a greater tendency to flex in the guiding system, which results in less accurate control of head trajectories.

* Such a magnetic coating defect would also impair the recording or replay of many adjacent tracks on the tape.

If the path followed by the replay head does not follow the recorded track, then a loss of replayed signal will occur. Depending on the geometrical arrangement of the recorded tracks, it is also possible that interfering signals from neighbouring tracks can be picked up by the reproduce head. This leads to an increase in the rate of errors during replay.

In video recording, the tape transport must also ensure that the heads are moved past the tape at a constant speed. In mechanical systems there are inevitable design limitations and tolerances that lead to variations in the head-to-tape speed. This results in frequency modulation of the reproduced signal that could give inaccurate clock recovery for data regeneration. Again, a contribution to errors in the output data stream is made.

5.1.3 Record—reproduce process

There are many sources of impairment associated with the process of recording and replaying signals from magnetic tape. The performance of heads for high recording density is far from ideal. They are difficult to manufacture consistently, are fragile, and their properties change as they become mechanically worn. As recording proceeds, magnetic interactions between neighbouring data bits on the tape cause non-linear distortion of the recorded waveform. During playback, the reproduced signal is impaired by noise caused by granularity in the recording medium, noise generated in the replay head, and noise added by the replay electronics.

The replay process produces a distorted version of the signal that was originally recorded. Linear distortion occurs at low signal frequencies because of the differential relationship between magnetic flux from the tape and induced voltage in inductive replay heads. At high frequencies distortion is produced by losses associated with the medium thickness and geometry of the replay head[10]. These distortions are reduced by an equalisation system, which attempts to restore the balance of low and high signal frequencies, without amplifying too much replayed noise. In practice, some distortion remains (called inter-symbol interference), which in combination with noise causes errors to occur in the replayed data stream.

The clock timing information recovered from the replayed waveform can also be a source of impairment. In addition to the head-to-tape speed fluctuations mentioned above, both noise and distortions remaining in the replayed waveform after equalisation can cause variations in recovered clock timing information. If the reproduced waveform is sampled at the wrong time, the rate of errors in the output data is increased.

5.2 Measures of performance

5.2.1 Error rate

As mentioned earlier, the basic measure of performance for a digital recording system is the rate of errors occurring in the replayed data. The rate of errors in the replayed output of a recorder can be determined by counting, if the original data is available. However, for good channels (or perhaps error-corrected channels), the error rate may be very low, so that counting errors is impractical. A method of estimating the error rate is required.

Using the simulation system, estimates of the replay error rate can be obtained from digitised analogue replay waveforms captured from the output of a recorder's equalisers. The procedure involves processing the digitised waveform with a software phase-locked loop, to recover the clock timing information. The voltage in the waveform at these instants is then interpolated from the available samples, and the results are sorted to form a histogram. The process is akin to taking a cross-section at the clock instant through the eye diagram formed by the waveform, as shown in Fig. 7.

If the cause of impairment in the recording channel is Gaussian noise, the histogram appears as two Gaussian curves separated by the signal amplitude. A simple data regenerator might compare the voltage in the reproduced waveform at the clock instants with a threshold, and decide that greater voltages correspond to recorded data of binary one, smaller voltages to binary zero. The threshold may be set to a value representing the average of the two binary signal values. For the software simulation, the two peaks in the histogram are separated at the point representing the average of means of the peaks, and their standard deviations are calculated. The error probability can then be estimated using the expression

$$Pe = \frac{1}{2}\ \mathrm{Erfc}\left(\frac{A}{\sqrt{2}.S}\right) \qquad (1)$$

where A is half the separation of the peaks,

S is the standard deviation of the peaks,

Erfc is the complementary error function.

which represents the area under a Gaussian probability distribution curve between a distance A from the mean and infinity. The argument of the error function is essentially the signal-to-noise power ratio replayed from the channel.

When the impairment in the channel is a mixture of noise and residual inter-symbol interference (ISI) left after equalisation, then the above expression leads to an over-estimate of the true error probability.

5.2.2 Error rate in the presence of inter-symbol interference

If ISI is present in the reproduce waveform, in addition to Gaussian noise, then the histograms may no longer be Gaussian in appearance. A fine structure appears, whose origin can be explained using Fig. 8. The vertical arrows represent the voltages at the clock instants due to the true data, with and without the ISI contributions from neighbouring data bits. The noise in the channel then causes a Gaussian spread in each of these discrete voltages, to give an overall histogram showing the modified Gaussian appearance. The figure shows a case of simple ISI from only the previous data bit. In practice, many neighbouring bits contribute different voltages, so that the histogram has a complex

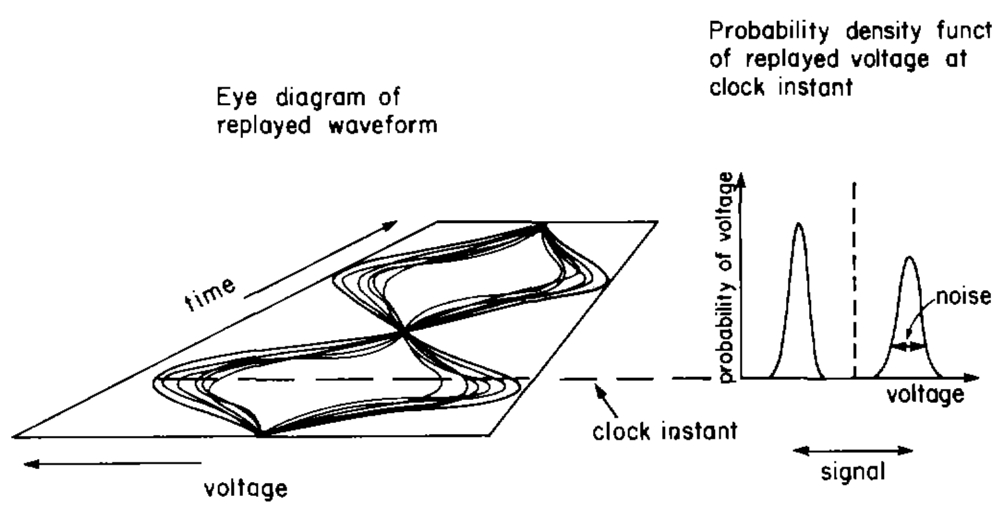


Fig. 7 - Estimating error rates from replayed waveforms containing noise.

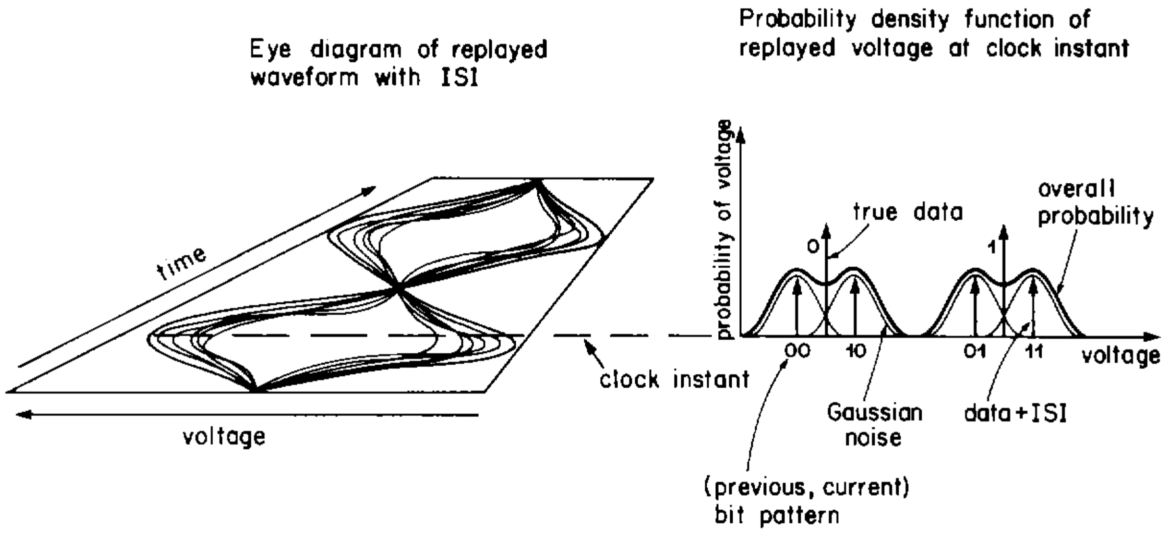


Fig. 8 - Estimating error rates for replayed waveforms containing simple inter-symbol interference and noise.

underlying fine structure, upon which the noise is superposed. Non-linear ISI, whose contribution to the reproduce voltage at the clock instant is proportional to the *product* of neighbouring bit values, can be treated in a similar way.

To estimate the error rate in a reproduce waveform containing linear and non-linear ISI, the values of the discrete voltages representing the true signal values plus the ISI contributions from neighbouring bits (and products of them) must be measured. In the simulation, this is achieved by the following procedure:

The original data values are first regenerated from the digitised waveform using a software phase-locked-loop and slicer. A window of N bits is then defined over which ISI will be considered. A search is made for occurrences of each of the 2^N different combinations of the N window bits, and the mean and standard deviation of the voltage corresponding to the central bit is measured, for each separate combination. If the N bit window is sufficient to encompass all the ISI contributions from neighbouring bits in the channel, then the average voltage of each combination corresponds to one element of the fine structure (shown with an arrow in Fig. 8). The standard deviation of that average is the residual random noise in the channel.

An estimate of the error probability for a channel with ISI can now be made as the sum of 2^N error function expressions similar to (1).

$$Pe = \frac{1}{2} \sum_{i=1}^{2^N} P_i \operatorname{Erfc} \left(\frac{|V_i - T|}{\sqrt{2}.S_i} \right)$$

where V_i is the average voltage of pattern i

S_i is the standard deviation of pattern i

T is the threshold voltage

P_i is the probability of occurrence of pattern i. For NRZ channel coding this is equal to $\frac{1}{2^N}$

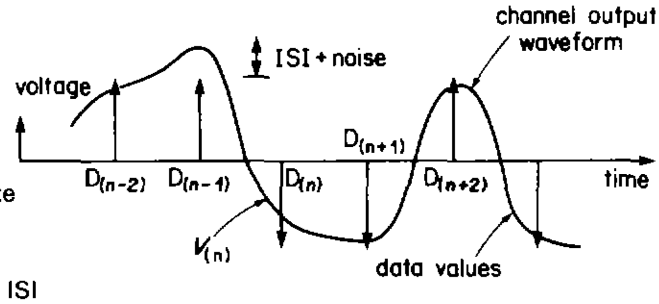
5.2.3 Inter-symbol interference power

The magnitude and proportion of linear and non-linear distortion in the reproduced signal can be estimated with software which extends the principle of the error-rate measurement described above. The reproduced waveform is expressed as a Volterra expansion of linear and product non-linear contributions from neighbouring bits in an N-bit window, as illustrated in Fig. 9(a). There are exactly 2^N terms in such an expansion (a DC term, a signal term, $N - 1$ linear terms and $2^N - N - 1$ non-linear terms). An example of such a Volterra expansion is given in Fig. 9(b), where a window of 3 bits (nearest neighbour ISI only) has been chosen for simplicity. The 2^N measured average pattern voltages and the 2^N Volterra terms form a set of simultaneous equations which can be solved completely. The solution gives the magnitude of each Volterra co-efficient.

Simply by picking out appropriate Volterra co-efficients, the signal-to-ISI ratio of a particular ISI mechanism can be calculated, and the proportion of linear and non-linear ISI can be assessed. It is also possible to calculate the signal-to-noise ratio in the absence of ISI, which could be taken as some measure of the maximum capacity of the channel[11].

This procedure is limited in application to

$$V_{(n)} = \sum_{r} A(\mathbf{r}) \prod_{j=-m}^{k} D_{(n+j)}^{r_j} + \text{noise}$$



where $V_{(n)}$ is the channel output voltage at time n/bit rate

$D_{(n+j)}$ $= \pm 1$ are the data values

$A(\mathbf{r})$ are co-efficients representing the strength of ISI

$k + m + 1$ $=$ N, the number of bits in the window

$\mathbf{r}$ is a vector with $(k + m + 1)$ components, $\mathbf{r}_{(-m)}, \mathbf{r}_{(-m+1)} \ldots \mathbf{r}_k$, where each component can be 0 or 1, representing the nature of the ISI. If a component $\mathbf{r}_j = 0$, then the contribution of $A(\mathbf{r})$ to $V_{(n)}$ does not depend on bit D_{n+j}.

Fig. 9(a) - Representation of channel output voltage at clock instant using Volterra series.

$V_{(n)} =$ A(000) +			.. D.C. term
D(n) . A(010) +			.. wanted signal
D(n−1) . A(100) +		D(n+1) . A(001) +	.. linear ISI
D(n−1) . D(n) . A(110) +	D(n) . D(n+1) . A(011) +	D(n−1) . D(n+1) . A(101) +	.. bi-product non-linear ISI
D(n−1) . D(n) . D(n+1) . A(111) +			.. tri-product non-linear ISI
NOISE			.. random noise

Fig. 9(b) - Volterra series expansion for nearest neighbour inter-symbol interference only.

recording systems where the channel coding used does not exclude data patterns that coincide with one of the 2^N in the defined N bit window. In this case the system of simultaneous equations cannot be solved independently for the Volterra co-efficients unless terms are dropped from the Volterra expansion.

5.2.4 Equivalent signal-to-noise ratio

In describing and comparing the properties of different recording systems, it is often helpful to express measured quantities in familiar units. The signal-to-noise ratio of a system is a widely used measure. For recording channels, the error probability can be described in signal-to-noise terms by referring to the signal-to-noise ratio of a distortionless channel containing stationary Gaussian random noise which gives the same error probability.

5.2.5 Safety margin

The safety margin for a digital channel can be defined as the difference in equivalent signal-to-noise ratio between the current operating point, and the point at which the error correction system begins to fail.

The size of the safety margin is very dependent on the design of the error-correction system, for a particular recording channel. This is because the properties of error-correction systems depend on the nature of the errors they are trying to correct. From magnetic tape, two classes of errors arise:

1. Background random errors caused by noise and distortion in the channel.
2. Bursts of errors caused by defects in the recording medium.

For a given error-correction system, it is fairly easy to determine the power of the code to correct either of the above classes of error, in the absence of the other. It is much more difficult to determine analytically (and to describe) the power of the code in correcting a mixture of the above types of error. However, computer simulation can be used to map the code properties numerically. An example of this process is given in Section 6.5, for a component video recorder.

5.3 Relative sizes of different impairments

The relative contribution of various impairments in a recording transport can now be compared in equivalent signal-to-noise terms. The error-rate estimation and ISI analysis procedures described previously are used, together with some additional simulation software which can automatically identify the position of a captured replayed waveform relative to the magnetic footprint* on the tape.

* The magnetic footprint is a term describing the physical layout of the track pattern that is recorded on a tape.

From a waveform captured from the output of the replay equalisers of a recorder (before slicing), at least five properties can be determined:

1. The proportion of random noise in the channel.
2. The proportion (and nature) of linear ISI.
3. The proportion (and nature) of non-linear ISI.
4. The variation of the signal-to-noise ratio along a replayed track, which can be used to assess the tracking accuracy of the transport.
5. The safety margin before error correction failure.

6. EVALUATING COMMERCIAL DIGITAL RECORDERS

In the following sub-sections, those aspects of performance of a digital recorder which are particularly important for broadcasting are discussed. How the simulation system has helped answer some of the questions raised is also described (with some examples), but detailed experimental results are beyond the scope of this Report.

6.1 Important performance factors for broadcast recorders

Leaving aside factors relating to convenient operational control, the rate of errors in replayed data is still the most important measure of a digital recorder's performance for broadcasting. However, the conditions under which error-free performance is required are more exacting than for other applications.

Constraints arise because recorders perform editing and multi-generation recording during programme making, in an environment which works most efficiently when tapes can be exchanged between different machines (perhaps from different manufacturers) with no penalty. A completed programme may be archived, for future re-use. Experience with analogue television recording suggests that archived programmes may be recalled after more than 25 years in storage.

The exchange of tape between machines made by different manufacturers demands that the magnetic. track pattern (or footprint) that is recorded on tape conforms to a published standard. This footprint must remain good after editing, which may have re-recorded some parts of the footprint while leaving other parts intact.

To maintain error-free performance after tape editing, the electrical and mechanical tolerances of the tape transport must be tighter than for recording and replay alone. This situation is merely exacerbated when tapes are exchanged between different machines.

Mechanical tolerances in a tape transport control the accuracy and consistency of its tracking geometry. This directly affects the ability of the heads of a replay machine to follow the track pattern laid down by a different record machine. It also affects the ability of a different machine to insert new recorded material into old with the same shaped tracks. Such inserts are often designed to erase any previous recording. If the tracking geometry of the insert does not match the original recording, unerased remnants of the previous data can remain which might interfere with the wanted signal when replayed. Fig. 10 illustrates this problem.

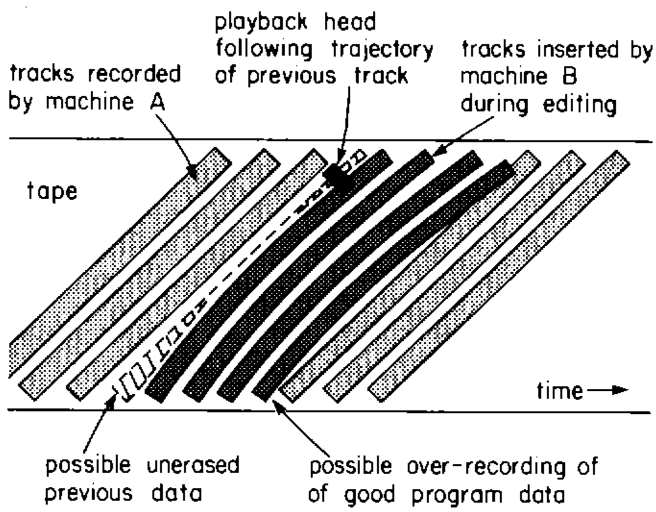
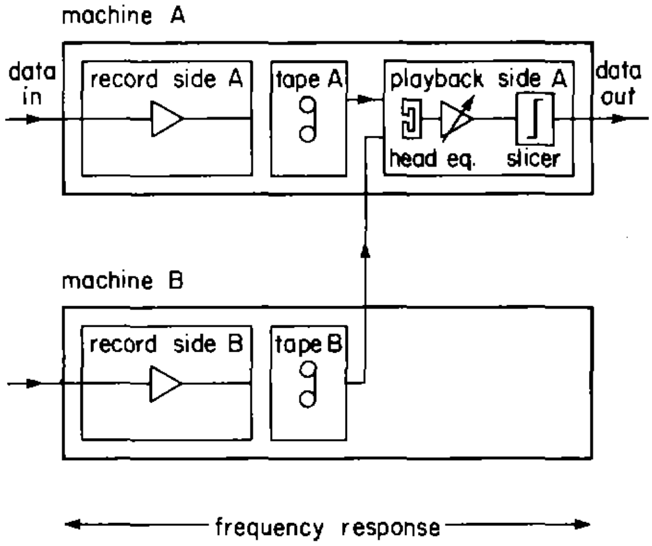


Fig. 10 - Record/replay problems caused by poor control of tracking geometry.

One particular electrical tolerance of interest concerns the frequency response of the recording channel, and the contributions which are made by stages on the record and the replay side of a machine. As noted earlier, a poor overall frequency response of a digital channel can affect the output error rate by causing inter-symbol interference. As illustrated in Fig. 11, when tapes are exchanged, the overall frequency response is composed of parts from the record side of one machine and the replay side of another. To ensure good overall frequency response (and so minimise ISI), the frequency response of the record and replay sides must be controlled separately. In practice, implementing such a specification is a problem, because of the difficulty in isolating a frequency response measurement for the record part of a channel.



$$\text{Response from tape A} = A_{RECORD} \times A_{PLAYBACK}$$

$$\text{Response from tape B} = B_{RECORD} \times A_{PLAYBACK}$$

$$\frac{\text{Response A}}{\text{Response B}} = \frac{A_{RECORD}}{B_{RECORD}}$$

Fig. 11 - Frequency response of playback waveform for interchanged tape.

The investigation of these factors using the simulation system is described in the following sub-sections.

6.2 Magnetic footprint

The magnetic footprint can be investigated by examining captured waveforms obtained from the replay equalisers. By capturing waveforms that are several tracks long, the relative positions of selected events can be determined quite accurately.

Fig. 12 shows some example waveforms captured from a D1 recorder. Fig. 13 shows some of the details of the D1 footprint[12]. With reference to this standard, software was developed for the simulation system which automatically identifies the positions of events such as the start of video and audio data areas in tracks. Confirmation of many aspects of the footprint can be achieved simply be measuring the relative distances between such positions.

Further checks can be carried out to verify that the footprint remains good after tape editing has been performed. A worst case example would be to measure the relative positions of the video and audio data blocks in a D1 recording where two of the four audio blocks have been re-inserted, but the remainder of the footprint remained intact.

Using the simulation system, the relative positional accuracy of events in a D1 footprint can be determined to within about one quarter of the minimum recorded wavelength over a distance spanning about 24 tracks. However, since time differences in waveforms are being used to infer distances on tape, measurement accuracy is reduced by variation in head-to-tape speed.

6.3 Error rate, impairment breakdown and safety margin

The simulation system has been used to estimate the error rate in a recording channel using the method described in Section 5.2. The degree to which the error rate is degraded by tape editing or interchange between different machines has been determined, along with the reduction in available safety margin. The source of the primary contributions to any such degradation in performance can now be resolved.

An example of the kind of results obtainable is given in Fig. 14. This shows the estimated error rate (expressed in equivalent Gaussian signal-to-noise ratio terms), for a D1 recording channel playing a tape recorded on a different machine. The particular pair of machines was chosen to show poor performance (and not a typical situation) for the purposes of illustration.

Using the Volterra analysis, the proportion of linear and non-linear ISI in a 9-bit window has been calculated, and used to estimate the error rate that would occur if either the linear, or both the linear and non-linear ISI in the window were removed. The variation of both along a replayed track is also shown. The safety margin of this playback signal could be expressed as the difference in equivalent signal-to-noise ratio of the working point of the recorder and approximately 10 dB, which is about the point at which the proportion of uncorrected errors in the D1 error correction system begins to rise sharply.

Near the beginning of the track, the safety margin is negligible, and the replayed signal is corrupted by errors. The manner in which signal-to-noise ratio varies is indicative of differences in tracking geometry between the record and replay machines (the tape could be replayed perfectly on the machine that recorded it).

6.4 Frequency response

The frequency responses of recording channels have been determined from waveforms captured from the output of the replay equalisation system. The method employed involves using the simulation software to recover the data that was originally recorded. The channel frequency response is then estimated by dividing the spectrum of the waveform at the output

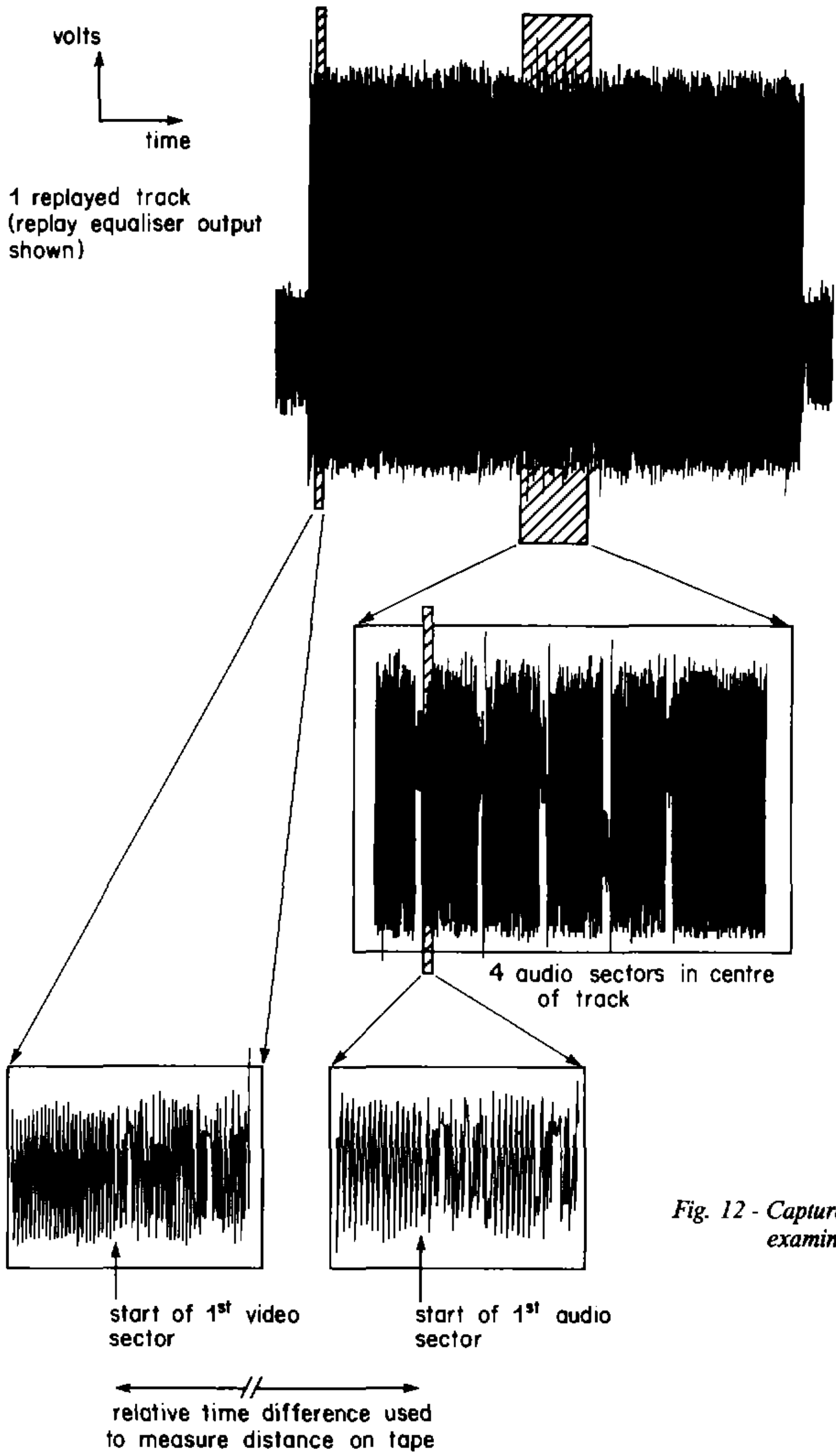


Fig. 12 - Captured waveforms from a D1 recorder examined for recording format.

of the equalisers by the spectrum of the recovered data which produced it. Fast Fourier transforms are used to compute averaged power spectra, and the coherence of the equalised waveform with the data is used to correct for noise added by the channel[13].

Using these frequency response measurements, it is possible to compare the contribution to the overall frequency response made by the record part of different channels alone (as illustrated in Fig. 11). Two recordings are made on different machines and are then replayed on the same machine. The overall frequency responses in both cases are estimated from waveforms captured from the output of the replayed equalisers. Since the contribution to the overall response from the replay side is now the same in both cases, dividing the two results gives the ratio of the frequency responses of just the record parts of the two

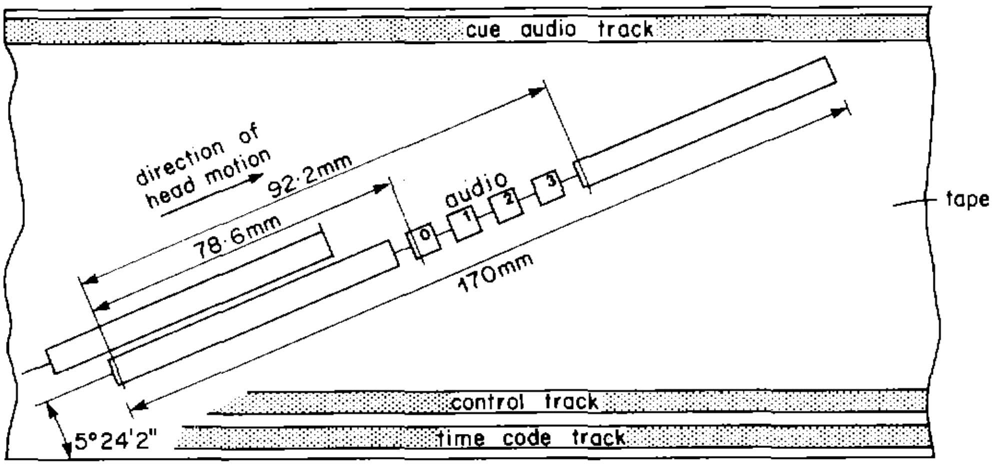


Fig. 13 - Magnetic footprint for D1 recording.

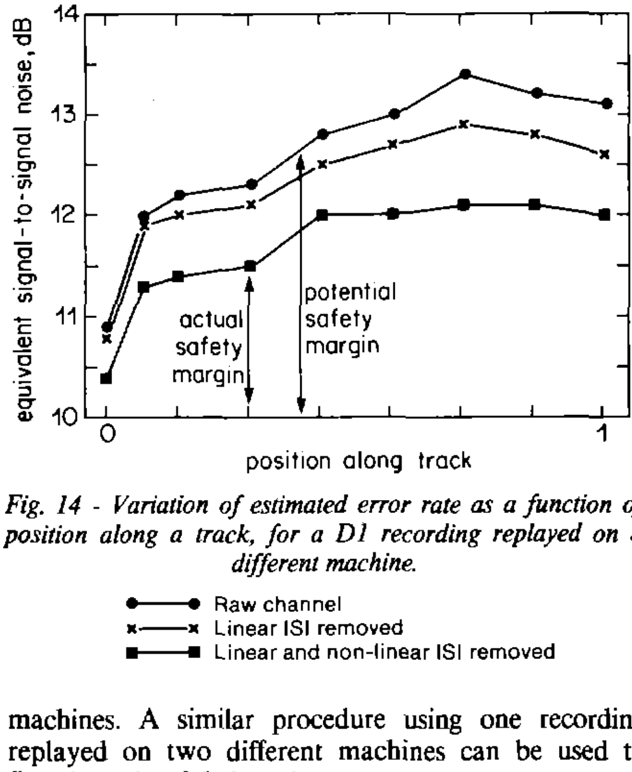


Fig. 14 - Variation of estimated error rate as a function of position along a track, for a D1 recording replayed on a different machine.

●——● Raw channel
×——× Linear ISI removed
■——■ Linear and non-linear ISI removed

machines. A similar procedure using one recording replayed on two different machines can be used to find the ratio of their replay responses.

If a reference recording can be defined, then a means for promoting tape exchange by separate control of the record and replay contributions to the frequency response has been established.

6.5 Error-correction system performance

Computer simulation can be used to map the error-correcting capability of a code as a function of various types of error. For example, the burst-error-correcting capability of the two-part Reed-Solomon code used in D1 recorders, under various burst and random error conditions, is shown in Fig. 15. The curve was obtained by counting uncorrected errors emerging from the (simulated) error-correction system, when a burst error of a certain size was inserted at the centre of a recorded sector. A given number of random errors were then added to the sector, with a

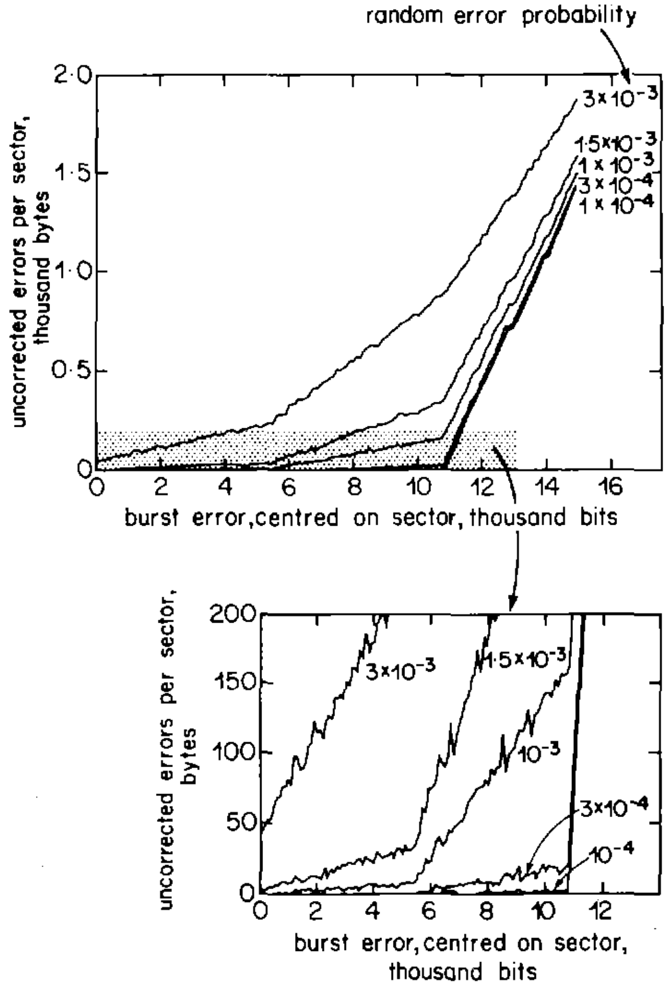


Fig. 15 - D1 burst error correction capability (random errors per sector as a parameter).

uniform probability distribution, and the uncorrected errors recounted. For that number of random errors added per sector, the uncorrected error count was averaged for 10 different random error distributions, to reduce anomalies produced by particular error distributions. It is notable that the maximum, burst-error-correcting capability falls sharply from its nominal value as the background error rate rises.

From this curve, the random error probability of 10^{-3} could be taken as the approximate point at which the proportion of uncorrectable errors rises sharply. This corresponds to an equivalent signal-to-noise ratio of about 10 dB.

6.6 Practical indication of margin

The factors discussed in this section highlight the need for a recording channel performance indicator which shows the available margin continuously while that channel is being used. Most commercial DVTRs have several independent recording channels, for video and audio. For operational reasons, such a performance indicator should be simple to read, and yet provide the ability to identify poor channels in multi-channel recorders, in cases where their margin is not equal. In this way, a prediction can be made for the likely failure of any given recording channel where the programme material is recorded and edited on different machines *before* the edit is performed. Potentially irreversible failures can then be avoided.

7. CONCLUSIONS

A simulation system has been described which uses a waveform digitiser and computer software to analyse electrical signals from the internal circuits of digital recording machines. Measurements made using the system can be used to assess the quality and predict the reliability of commercial digital video recording equipment.

Several common sources of impairment in digital magnetic tape recording have been discussed, which reduce the potential for error-free recording. A method of using the simulation to provide a quantitative breakdown of the contribution of each one to the overall performance of a recorder has been described. A measurement has been defined that indicates the safety margin in a machine's performance, which if eroded would lead to errors in data reproduction. By comparing the available margin with the sizes of known impairments, a feeling for the sensitivity of the status of a 'perfect recorder' can be obtained.

For broadcast purposes, the important factors which determine the performance of digital video tape recorders are different to those for other applications. The efficiency of a television recording operation depends on tape editing, multi-generation recording and tape exchange between different machines. In this respect, the simulation system has been used to identify and examine several issues, which include the use of:

1. Standard recorded track patterns on tape.
2. Tape transports with accurate and consistent mechanical properties.
3. Controlled frequency response of the recorded signal.
4. Adequate replayed signal-to-noise safety margin for error correction.

The simulation system also provides a framework for optimising design strategies in the development of new high-density recorders, without the need for building dedicated electronic hardware each time. Designs can be simulated in software and evaluated on signals taken from real systems. The convenience and flexibility of this approach makes it useful in a wide range of data recording, or transmission applications.

8. REFERENCES

1. LUNN, J.D., MOFFAT, M.E.B. 1969. Possible techniques for recording of digital television signals. BBC Research Department Report No. BBC RD 1969/42.
2. JONES, A.H. 1973. Digital television recording: a review of current developments. BBC Research Department Report No. BBC RD 1973/29.
3. BELLIS, F.A. 1976. An experimental digital television recorder. BBC Research Department Report No. BBC RD 1976/7.
4. BELLIS, F.A. 1979. A multichannel digital sound recorder. BBC Research Department Report No. BBC RD 1979/15.
5. BELLIS, F.A. and PARKER, M.A. 1986. An experimental helical scan DVTR. BBC Research Department Report No. BBC RD 1986/15.
6. NEWBY, P. and WOOD, R. 1986. The effects of non-linear distortion on Class IV partial response. *IEEE Trans. Magn* (USA), Mag-22, No. 5.

7. MALLINSON, J.C. and STEELE, C.W. 1969. Theory of linear superposition in tape recording. *IEEE Trans. Magn*, Mag-5, 886.

8. MEE, C.D. and DANIEL, E.D. (ed). 1987. Magnetic recording, Volume 1: Technology. Chapter 2, by Middleton, B.K. McGraw-Hill.

9. International Electrotechnical Commission. 1988. Helical-scan video cassette recording system using 19 mm magnetic tape (Format D-2). DRAFT document.

10. JORGENSEN, F. 1980. The complete handbook of magnetic recording. TAB Books.

11. WILLIAMS, C.H. 1990. Measurement and classification of impairment for DVTR transports. Eighth International Conference on Video Audio and Data Recording. *IEE Conference Publication No. 319*, pp 67-78

12. EBU. 1986. Standard for recording digital television signals on magnetic tape in cassettes. EBU Tech. 3252-E.

13. BENDAT, J.S. and PIERSOL, A.G. 1980. Engineering applications of correlation and spectral analysis. Wiley.

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